

Research on Concrete Aggregates

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INTRODUCTION

Portland cement concrete has been used extensively for many years as a construction material in bridges, buildings, highway pavements and other structures. Numerous structures and pavements that have been in service for decades illustrate the good durability and value of concrete when properly used in engineering construction. For example, the first concrete pavement built in the United States was still in use and in good condition after more than 50 years (1)*.

Like any other engineering material, concrete will fail structurally if subjected to overloads. Durability, as used in this paper, refers to the ability of the concrete to withstand the attack of natural agents of weathering and deterioration, without consideration of the structural adequacy of the material to carry the loads to which it is subjected. Figures 1 and 2 illustrate the excellent performance obtained from hundreds of miles of concrete pavement and many structures in Indiana.

Although concrete has, in general, proven to be a durable material, there are many examples of non-durable concrete—concrete that has failed or deteriorated because of the effects of natural weathering or chemical reactions. Unsightly cracking, spalling, scaling and pop-outs, as well as general crumbling, disintegration and failure of concrete structures may be observed in all sections of the country. The concrete with poor durability characteristics represents only a small percentage of the pavements and structures that have been built, however, the cost due to decreased life of the concrete is a very important item (2). The financial losses, inconveniences, and in some cases, dangers to the public that may result from only an occasional failure have led to extensive work and study in the field of concrete durability.

Many and varied reasons for failure of concrete structures have been shown to exist. When we consider that portland cement is an ex-

* Numbers in parentheses refer to references appended to this paper.



FIGURE 1. A 20-year old Indiana Concrete pavement that is in perfect condition with no evidence of deterioration of any kind.

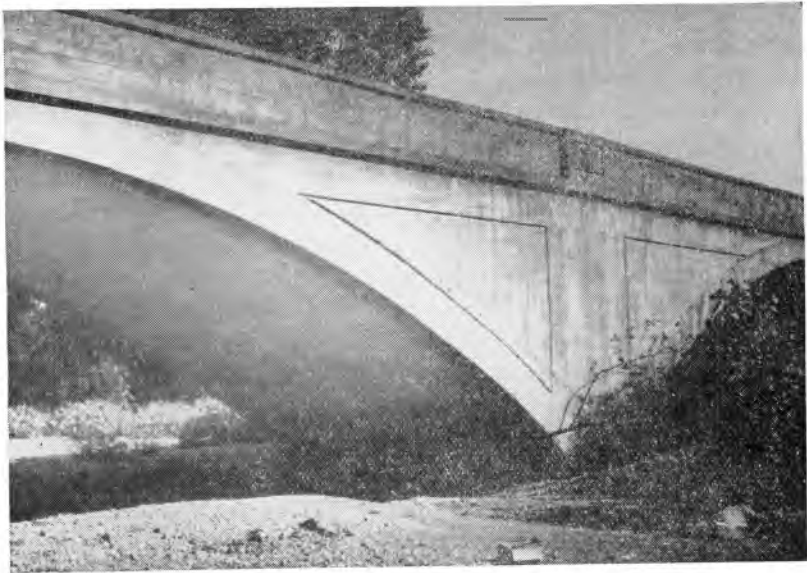


FIGURE 2. A concrete bridge that is unaffected by weathering after 42 years of exposure.

tremely variable material both in chemical composition and physical properties; that the aggregates used may vary greatly in gradation, soundness, absorption, and other physical and chemical properties; and that both design and workmanship in construction affect the quality of the concrete; it is evident that many factors must be considered in evaluating the durability characteristics of concrete. The effect of the factors of design and workmanship on durability are subject to control by proper care in design and construction. The other factors affecting concrete durability may be grouped under the category of unsound or inferior materials and present problems that have not been completely solved. Either the cement or the aggregates, or a particular combination of cement and aggregate, may have physical or chemical characteristics that result in unsound, non-durable concrete.

During the past 10 or 15 years the recognized problems of concrete durability, as affected by the materials used, have been described in great detail in the technical literature. Therefore, except for the problem in the Midwest area (Indiana and adjacent states), they will be described only briefly here.

In the West and South the major problem is apparently due to a chemical reaction between certain aggregate constituents and the alkalis in the cement which produces expansion, cracking and disintegration of the concrete (3, 4, 5, 6, 7). Concrete deterioration found in the Great Plains area has been attributed to a cement-aggregate reaction which is not due to the cement alkalis alone (8). Other work has shown that this disintegration can be produced in the laboratory by cycles of wetting and drying of the concrete specimens (9), indicating that the moisture absorption and expansion characteristics of the materials might be partially responsible for the trouble. In some parts of the East the failure of some concrete has been attributed to unsound fine aggregates (10). The major problem of non-durable concrete in the Midwest is characterized in the field by D-lines, mapcracking and blowups of pavements and general cracking and deterioration of structures. The deterioration is associated with the use of certain coarse aggregates and is apparently due to excessive expansion of the aggregates when frozen in a saturated condition (11, 12, 13). Figures 3 and 4 show typical deterioration of concrete in which such aggregates have been used.

The fact that the aggregates, which constitute a very large portion of a concrete mix, are involved in all of the major problems of concrete durability mentioned above has led to a great deal of research on the properties of concrete aggregates. It should also be noted, that although problems of the influence of aggregates on concrete durability



FIGURE 3. Concrete pavement made with inferior coarse aggregate after 13 years.

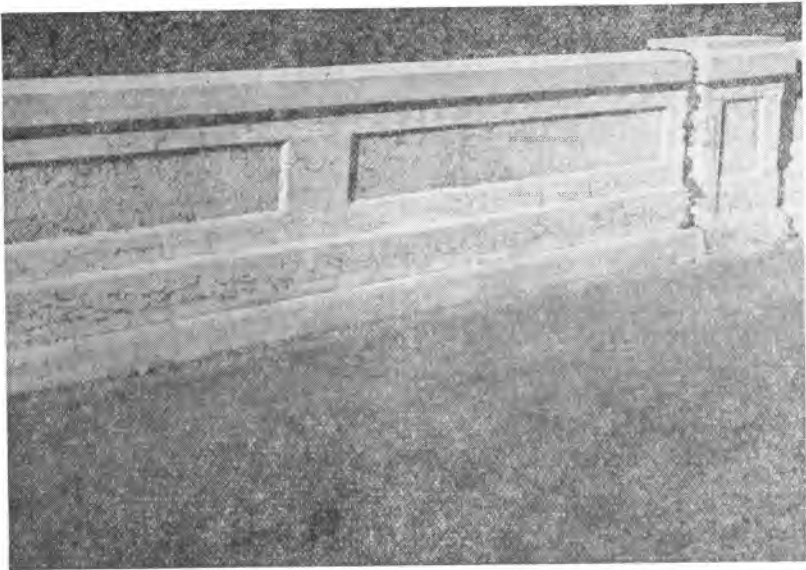


FIGURE 4. Appearance of a 20-year old bridge *railing* in which a deleterious aggregate was used.

are nation-wide, the specific problems vary in different areas. A solution to the problem in one section of the country will not necessarily be of value to other regions.

The magnitude and diversity of the problems have resulted in a great amount of research by many organizations—agencies of the Federal Government, technical and scientific societies, state highway departments, universities and colleges, and commercial organizations.

A large amount of research work on Indiana aggregates as related to the durability of concrete has been carried on by the Joint Highway Research Project in recent years and the results of many of the individual studies have been described in detail in published papers (13, 14, 15, 16, 17, 18, 19). General conclusions based on the published work will be summarized here, followed by more detailed descriptions of recently completed (unpublished) and current studies.

PREVIOUS INVESTIGATIONS

A paper by Lewis and Woods (19) presented at the Thirty-fifth Annual Purdue Road School summarized the field and laboratory investigations of concrete durability in the Midwest with the previous work on Indiana materials discussed in considerable detail. The field and laboratory studies discussed show that a definite problem of concrete durability, which has been correlated in many instances with the sources of coarse aggregates used, exists not only in Indiana but throughout the Midwest. The inadequacy of standard methods of test and the need for new tests and specifications to differentiate between good and bad aggregates for use in portland cement concrete were noted.

On the basis of all the research work on Indiana aggregates that had been completed at that time, the following major conclusions were drawn:

1. The effect of freezing and thawing on some materials in a highly-saturated state is the primary factor in their lack of durability in concrete. The absorption and pore or void characteristics of the materials determine their susceptibility to this type of damage.
2. Correlations with field performance records justify consideration of the following tests for use in quality specifications of crushed stone for concrete aggregate:
 - a. Percentage of voids less than 0.005 mm. in diameter based on microscopic studies.
 - b. Absorption and degree of saturation of the aggregate under vacuum. Proper consideration should be given the probability of the materials attaining high saturation by this test but not under field conditions. Apparently the "quarry-wet" degree of saturation, the ratio of 24-hour absorption to evacuated

absorption, and the void size characteristics all furnished an indication of this.

- c. Freezing and thawing tests of concrete in which the aggregates are incorporated in a saturation condition comparable to the degree of saturation that may be attained in field use. Comparative tests should be used, with the unknown material compared to an aggregate of known services durability. Proper control of air content and degree of saturation of the mortar would be necessary.
3. If, for economic reasons, it seems desirable to use a doubtful or inferior aggregate, the concrete durability may be improved by:
 - a. Use of air entrainment.
 - b. Drying of aggregates before incorporation in the concrete.
 - c. Use of base courses, subgrade drainage, summer construction, etc., to insure that the concrete becomes and remains as dry as possible before freezing and thawing begins.

The conclusions quoted above apply specifically to crushed stone aggregates. The majority of the laboratory investigations made were on crushed stone and additional research is needed before the results can be extended to include gravels.

RECENT STUDIES

During the past year, three research studies on Indiana aggregates have been completed in the Joint Highway Research Project laboratories. The projects were carried out by graduate students who used them as thesis subjects in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering. The studies to be discussed here are "The Effect of Restraint on the Durability of Concrete Aggregates" by L. C. Pendley, "Influence of Fine Aggregates on Concrete and Mortar Durability" by J. G. Higgs, and "Determination of Pore Size of Four Indiana Limestones" by F. K. Fears.

EFFECT OF RESTRAINT ON DURABILITY OF CONCRETE AGGREGATES (20)

Many highway engineers advocate the construction of continuously-reinforced concrete pavements. No expansion joints are used, and the rather heavy reinforcement is continuous across all other joints. Several states, including Indiana, have experimental test sections of this type of pavement. Such a design would be expected to impose considerable external and internal restraint on expansion of the concrete.

This study was undertaken to determine: (a) the effect of such restraint on the durability of the concrete, particularly with inferior coarse aggregates, (b) the effect of varying amounts and sizes of

reinforcing steel, and (c) the effect of using an expanding cement which would impose even more restraint by decreasing the shrinkage cracking of the concrete.

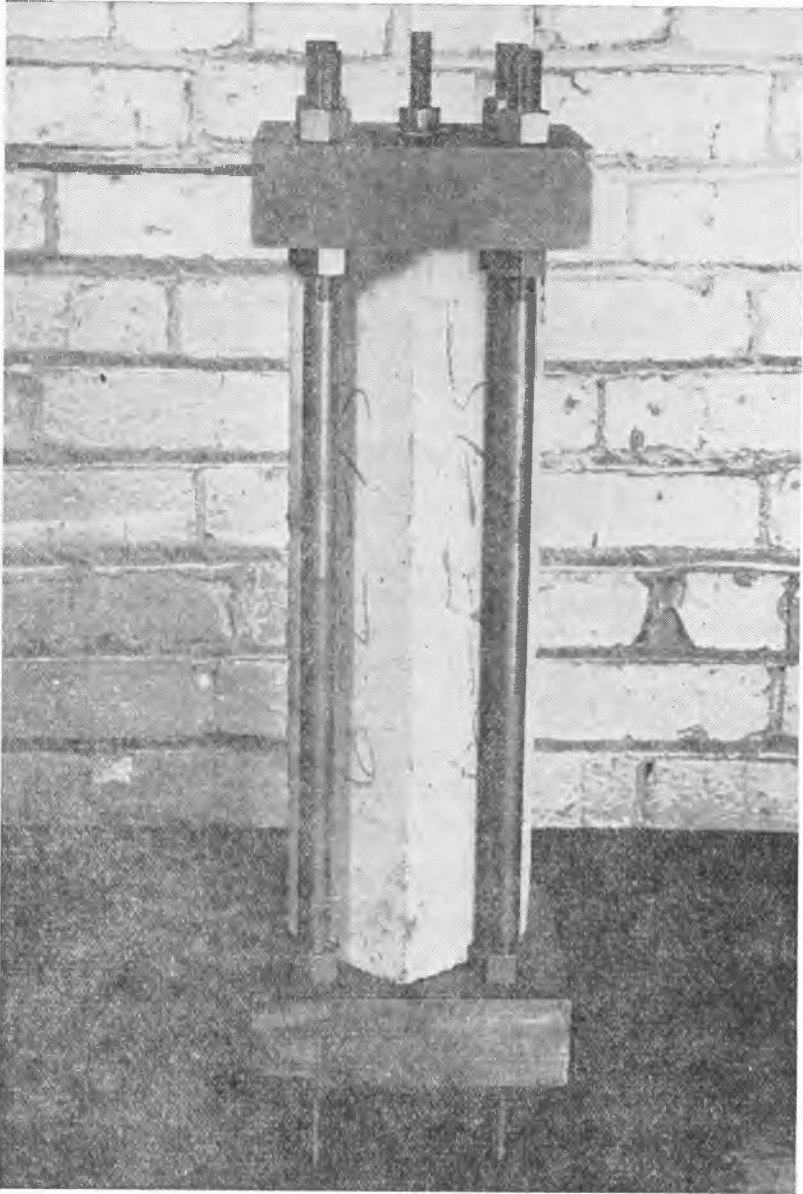


FIGURE 5. Reinforced concrete beam in the steel frame restraining device.

The aggregates used in the tests included four coarse aggregates, gravel and stone with both good and bad field performance records and a single fine aggregate that was used for all mixes. One Type I cement was used, but was modified by adding Vinsol Resin and calcined gypsum to produce, respectively, an air-entraining and an expanding cement for use in some of the tests. Some of the 4x4x16-inch specimens tested were not reinforced, while others contained a single longitudinal bar of reinforcing steel. Five sizes of round bars, from $\frac{1}{4}$ to $\frac{3}{4}$ inches in diameter were used.

The proportions of the concrete mixes and the mixing and curing procedures were the same as those used in previously reported studies. After curing, part of the beams were placed in a steel restraining device (see Figure 5) and subjected to a load of 500 lbs./sq. in. Freezing and thawing tests were then run on both restrained and unrestrained beams from each concrete mix. The majority of these tests were conducted at temperatures of -18° and 135°F. , with changes in the dynamic modulus of elasticity being used as a measure of deterioration of the concrete.

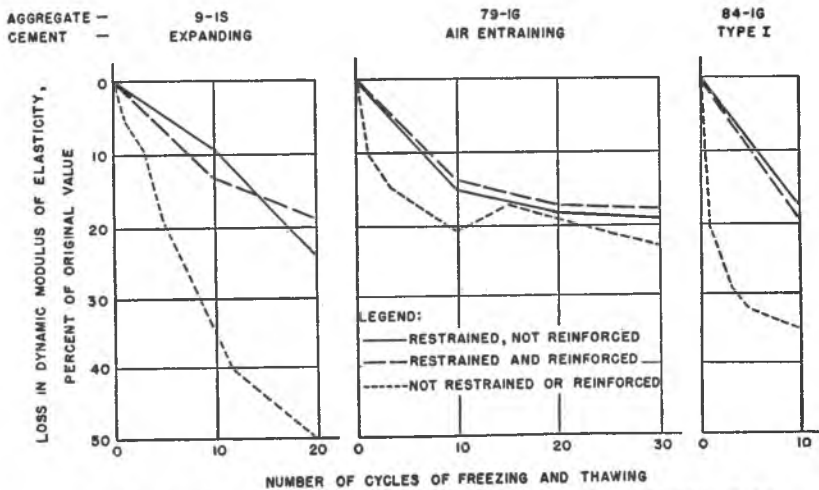


FIG. 6. TYPICAL RESULTS OF TESTS ON THE EFFECT OF RESTRAINT ON CONCRETE DURABILITY.

Figure 6 shows typical results obtained in this study, illustrating the relative rates of deterioration obtained with several different aggregates and cements. The major conclusions reached as a result of this investigation were:

1. With the single exception of a poor-performing limestone with air-entraining cement, restraint of the concrete decreased de-

terioration in freezing and thawing. The greatest improvements in durability were obtained with the aggregates having the poorest durability without restraint.

2. Neither the presence of nor the amount of steel reinforcement affected the durability of the concrete significantly.
3. The durability of concrete made with expanding cement was improved markedly by restraint, as compared to mixes with the other cements.
4. The increase in durability of restrained beams was apparently due to the prevention of cracking perpendicular to the longitudinal axis of the beam. The crack pattern in restrained beams was parallel to the beam axis as compared to a random pattern in unrestrained beams.

In the construction of concrete pavements in Indiana, a design without transverse joints was used prior to 1935. Both expansion and contraction joints were used following this time until the past few years when contraction joints only have been installed. More restraint of expansion would be expected in the older non-jointed pavements than in those with expansion joints. That such a condition exists is shown by the numerous blowups (buckling from excessive expansive forces) on roads constructed with inferior aggregates and no joints as compared to those with similar materials and expansion joints. Cracking and disintegration in the field invariably begins at joints and cracks and there appears to be some indications in the existing pavements that this deterioration is more rapid in cases where frequent expansion joints were employed.

Definite evaluation of this condition will probably be impracticable because of the effects of varying pavement age and other variables. Both field observations and the results of this laboratory study would indicate that the use of non-jointed and/or continuously reinforced pavements with inferior aggregates would result in more blowups and a slower rate of actual disintegration of the concrete, as compared to a pavement with frequent expansion joints.

INFLUENCE OF FINE AGGREGATES ON DURABILITY (21).

Positive correlation of coarse aggregates with field durability of concrete pavements in Indiana resulted from the early performance survey work (14). The effects of the fine aggregates could not be so clearly established, however, since some of them had been used only with the inferior coarse aggregates and the deterioration found might have been partially due to the fine aggregate used. In all previous laboratory work, a standard fine aggregate had been used in order to

eliminate any possible variations from this material. The study of fine aggregates was set up to determine what effect, if any, the Indiana materials had on the durability of both concrete and mortar.

Seven Indiana sands, ranging in source from dredged river deposits from the southern part of the state to glacial deposits in the northern part, were used. The materials are believed to be representative of Indiana fine aggregates, and are associated with gravels ranging from good to bad in field performance ratings. Some mixes were made using graded Ottawa Sand as the fine aggregate. Three coarse aggregates were used, representing both good and bad field-performing aggregates. Other variables included in the study were a wide range in air contents and three different laboratory weathering cycles—freezing in air and thawing in water, freezing in water and thawing in water, and alternate heating and cooling without freezing.

The concrete mixes were designed to correspond to those used in previous work, and the mortars tested were of approximately the same composition as the mortar in the concrete mixes. Specimens were 3x4x16 inches in size for the concrete mixes and 2x2x11 inches for the mortars. Standard mixing and curing procedures were followed throughout the study, and the temperature ranges used in the durability tests were -18° to 50° F. for freezing and thawing and 35° to 130° F. for the heating and cooling tests. Changes in dynamic modulus of elasticity and flexural strength were used to measure deterioration.

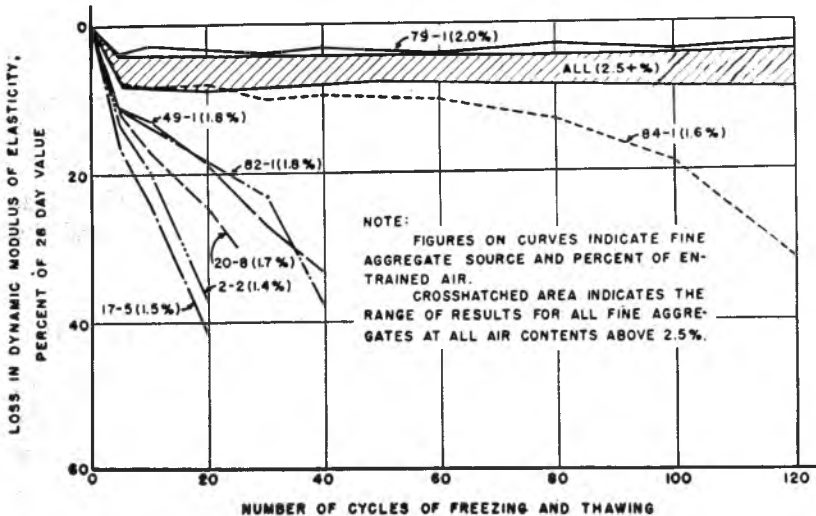


FIG. 7. TYPICAL RESULTS OF FREEZING AND THAWING TESTS ON CONCRETE MADE WITH A GOOD COARSE AGGREGATE (67-2S) AND VARIOUS FINE AGGREGATES.

Typical results of tests with a good-performing coarse aggregate and various fine aggregates are shown in Figure 7. No consistent or significant trends dependent upon the type of weathering cycle were found; therefore, the results shown are only for the regular test of freezing in air and thawing in water. Calculations of the mortar saturation indicated that none of the mixes were saturated, leaving only the fine aggregate itself as a variable that could have caused the durability differences.

The important conclusions reached from the results of this study were:

1. In concrete containing a durable coarse aggregate, the fine aggregates influenced the durability of the concrete when the air content was less than 2 percent. At higher air contents (above 2.5 percent) the effect of the fine aggregate on durability was negligible.
2. In concrete containing an inferior coarse aggregate, the influence of the fine aggregate on the durability is negligible compared to the effect of the coarse aggregate.
3. The durability of the mortars tested was dependent upon the fine aggregate at air contents less than 6 percent.
4. Present highway specifications requiring air entrainment in pavement concrete provide for sufficient air to eliminate the fine aggregate variable.

It is of interest to note that similar results and conclusions were reached by Walker and Bloem (22) in a study that was reported just prior to completion of the work described above. No failures have been observed in the field when a good coarse aggregate was used and it is probable that most of the concrete used in the past has contained small percentages of air. Certainly there is no reason to believe that the fine aggregates have had any major influence on the durability of concrete pavements in Indiana.

DETERMINATION OF PORE SIZE OF INDIANA LIMESTONE (23)

The original correlation of the volume of pores less than 0.005 mm. in diameter in limestone aggregates with field performance (13) aroused considerable interest in the possibility of devising an acceptance test based upon this property of the aggregates. The preliminary work, however did not include any investigation of the methods for determination of pore size. The limits of accuracy of the determinations and accurate figures on time involved in making such a test were likewise

unavailable. This study was initiated to investigate these factors and to evaluate the test method for use in acceptance testing of aggregates.

Four limestone aggregates were used in the study, two with good and two with bad field performance records. The general testing procedure consisted of the following steps:

1. Determination of the total void space in the aggregate by the relationship of absorption and apparent specific gravity to true specific gravity.
2. Preparation of thin sections and polished sections of the stone for study by transmitted, polarized light and reflected light, respectively.
3. Preparation of scale drawings of pores in the polished sections by means of a microscope and camera lucida attachment, and photomicrographs of the thin sections.
4. Measurement of the area of pores more than 0.005 mm. in diameter by planimetric methods and determination of pore space smaller than 0.005 mm. by the difference between the total porosity and the measured larger pore space.

Statistical analyses of the data were made to determine the limits of accuracy of the test results and careful records of the time required to run the tests were kept. Table I shows general results obtained in the study by use of the polished sections.

The information obtained led to the following conclusions:

1. The correlation of micro-porosity with aggregate performance is substantiated. The volume of pores less than 0.005 mm. in diameter was four to six times as large in the bad as in the good performing aggregates.
2. The polished section method is superior to that using thin sections.
3. Forty or more observations (measurements of pores in individual microscopic fields) are required to obtain an accuracy of ± 10 percent for measured areas of large pores (probability of 0.9). The best procedure was to determine the total void ratio of a large sample and then make the microscopic observations on pieces of stone selected at random.
4. The test is time consuming. Approximately 55 hours are required per sample. If a quarry with six to eight different ledges were to be tested, the testing time involved could readily amount to 400 or more man-hours.

The accuracy obtained in the test was determined on the basis of the measured areas of large voids. Since the voids smaller than 0.005 mm. are obtained by difference, the actual numerical range for their

TABLE 1
RESULTS OF DETERMINATIONS OF PORE SIZE OF INDIANA LIMESTONES

Aggregate Source	Field Performance Record	Pore Volume*			Probable Accuracy of Measured Values**	Number of Observations
		Total	Larger than 0.005 mm. dia.	Smaller than 0.005 mm. dia.		
67-2S	Good	0.041	0.024	0.017	12.3	48
1-1S	Good	0.066	0.044	0.022	7.7	48
9-1S	Bad	0.240	0.143	0.097	10.4	40
47-2S	Bad	0.108	0.026	0.082	9.1	40

* Expressed as a ratio of volume of pores to volume of solids.

** Plus or minus accuracy in percent of average measured values for pores larger than 0.005 mm. in diameter, based on 0.9 statistical probability.

volume would be the same as that for the large voids. The percentage error in volume of the small voids would be dependent upon the relative volumes of large and small pores and, in many cases, would be much greater than the ± 10 percent indicated for the larger ones. The great amount of time and number of observations required to obtain reasonable accuracy of results makes this test procedure unsatisfactory for acceptance testing.

The characteristics of the pore space in an aggregate—the size, shape, distribution, and continuity of the voids or pores—to a large extent control the durability of the material. These pore characteristics determine the water absorption and retention properties of the aggregate and are, therefore, very important in determining the damage that can be done by freezing and thawing. Present methods of study of the pore characteristics are inadequate and, for thorough understanding of their effects on durability, and methods for determination of the undesirable characteristics of pore systems, new test techniques are needed.

CURRENT STUDIES

Despite the great amount of data and information that has been obtained on the effects of Indiana aggregates on the durability of concrete, much work is yet to be done on the problem. Several investigations such as the determination of absorption and degree of saturation values for various aggregates, heating and cooling tests of concrete specimens, freezing and thawing at varying temperatures, additional field performance surveys, etc., are being continued to obtain data on other materials and to evaluate testing techniques.

One of the problems of great immediate importance is a comprehensive study of gravels. Some of the questions that need to be answered concerning these materials are: (a) What are the deleterious constituents in gravels? (b) How can they be identified? (c) What are their physical properties? and (d) What percentage of such constituents can be allowed without serious effect on the durability of the concrete? The first part of a major research program on gravels is currently being started. It will consist of testing each component of the gravels, separated on the basis of both type of rock and specific gravity. It is to be hoped that the answer, at least to the question of what the deleterious constituents of gravels are, will be found through this study. Additional phases of the gravel research program will be begun as time and facilities permit.

SUMMARY

The extensive field and laboratory investigations of the influence of aggregates on the durability of concrete indicate that:

1. Problems of concrete durability involving the quality of the aggregates are widespread throughout the country.
2. New tests and specifications are needed to differentiate between good and bad materials since the commonly-used acceptance tests are inadequate for this purpose.

The data available on Indiana aggregates from the large amount of field and laboratory research that has been carried on in recent years leads to the following conclusions:

1. Freezing and thawing of some coarse aggregates when saturated is the major factor in lack of durability of the concrete in which they are incorporated. The susceptibility of the materials to damage of this type is determined by their pore and void characteristics.
2. Indiana fine aggregates probably have little effect on the durability of the concrete in field use.
3. Field performance records of crushed stone aggregates have been correlated with:
 - a. Percentage of voids less than 0.005 mm. in diameter in the aggregate.
 - b. Absorption and degree of saturation of the material under vacuum.
 - c. Freezing and thawing tests of concrete in which the aggregates are used.
4. Since both the void size determinations and the freezing and thawing tests are very time consuming, the absorption and degree of saturation tests are the most practicable for present use in acceptance testing.
5. If inferior aggregates are used in concrete, the durability apparently may be improved by:
 - a. Use of air entrainment.
 - b. Drying the aggregate before use.
 - c. Use of construction practices that will aid in keeping the concrete dry.
 - d. Restraint of the concrete by means of continuous reinforcement and/or elimination of expansion joints.

As noted previously, the investigations are continuing and a comprehensive research program on gravels is being initiated in order to extend and increase the value and usefulness of the data available. It is believed, however, that proper utilization of the information now available, will result in the elimination of most of Indiana's very bad coarse aggregates from future use in concrete.

BIBLIOGRAPHY

1. Bartholomew, T., "First Concrete Paving 50 Years Old", *Engineering News-Record*, August 28, 1941, pp. 57-59.
- * 2. Woods, K. B., Blackburn, J. B., and Lewis, D. W., "The Use of Waterproofing Paints for Minimizing Structural Concrete Deterioration". Paper presented before the AREA Annual Convention, Chicago, Illinois, March, 1950.
3. Stanton, T. E., "Expansion of Concrete Through Reaction Between Cement and Aggregate", *Proceedings*, American Society of Civil Engineers, December, 1940, p. 1781.
4. Stanton, T. E., "Studies to Develop an Accelerated Test Procedure for the Detection of Adversely Reactive Cement-Aggregate Combinations", *Proceedings*, American Society for Testing Materials, V. 43, p. 875 (1943).
5. Tremper, B., "Evidence in Washington of Deterioration of Concrete Through Reactions between Aggregates and High-Alkali Cements", *Journal*, American Concrete Institute, June, 1941; *Proceedings*, V. 37, p. 673.
6. Hanna, W. C., "Unfavorable Chemical Reactions of Aggregates in Concrete and a Suggested Corrective", *Proceedings*, American Society for Testing Materials, V. 47 (1947).
7. Mielenze, R. C., and Witte, L. P., "Tests Used by the Bureau of Reclamation for Identifying Reactive Concrete Aggregates", *Proceedings*, American Society for Testing Materials, V. 48, pp. 1071-1103, (1948).
8. Scholer, C. H., and Gibson, W. E., "Effect of Various Coarse Aggregates upon the Cement-Aggregate Reaction", *Journal*, American Concrete Institute, V. 19, N. 10, June, 1948, pp. 1009-1032.
9. Jackson, F. H., and Kellerman, W. F., "Volume Changes in Sand-Gravel Concrete", *Proceedings*, Highway Research Board, V. 22, p. 252, (1942).
10. "A Digest of the Reports Covering a Study of the Causes of Deterioration of Concrete and Means of Prevention in the State Highway Systems of New York and Pennsylvania," Portland Cement Association, 1941.

* Source referred to includes an extensive bibliography on aggregate and concrete durability.

11. Cantrill, C., and Campbell, L., "Selection of Aggregates for Concrete Pavement Based on Service Records," *Proceedings, American Society for Testing Materials*, V. 39, p. 937, (1939).
12. Wray, F. N., and Lichtefeld, H. H., "The Influence of Test Methods on Moisture Absorption and Resistance of Coarse Aggregate to Freezing and Thawing", *Proceedings, American Society for Testing Materials*, V. 40, p. 1007, (1940).
- *13. Sweet, H. S., "Research on Concrete Durability as Affected by Coarse Aggregate", *Proceedings, American Society for Testing Materials*, V. 48, pp. 988-1016, (1948).
14. Woods, K. B., Sweet, H. S., and Shelburne, T. E., "Pavement Blowups Correlated with Source of Coarse Aggregate", *Proceedings, Highway Research Board*, V. 25, p. 147, (1945).
- *15. Sweet, H. S., and Woods, K. B., "Mapcracking in Concrete Pavement as Influenced by Soil Textures", *Proceedings, Highway Research Board*, V. 26, p. 286, (1946).
- *16. Sweet, H. S., and K. B. Woods, "A Study of Chert as a Deleterious Constituent in Aggregates", *Engineering Bulletin of Purdue University*, Research Series No. 86, September, 1942.
17. Bugg, S. L., "Effect of Air Entrainment on the Durability Characteristics of Concrete Aggregates", *Proceedings, Highway Research Board*, Vol. 27, 1947, p. 156.
18. Blackburn J. B., "Freeze and Thaw Durability of Air-Entrained Concrete Using Indiana Aggregates", *Proceedings, Highway Research Board*, V. 28, 1948.
- *19. Lewis, D. W., and Woods, K. B., "Research as Related to Aggregate Specifications", *Proceedings, 35th Annual Road School Extension Series No. 69* Purdue University, 1949, pp. 155-173.
20. Pendley, L. C., "The Effect of Restraint on the Durability of Concrete Aggregates", *Thesis*, submitted to Purdue University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, June, 1949.
21. Higgs, J. G., "Influence of Fine Aggregates on Concrete and Mortar Durability", *Thesis*, submitted to Purdue University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, February, 1950.
22. Walker, S., and Bloem, D. L., "Study of Sands in Concrete Subjected to Freezing and Thawing (Series 96)", *Circular No. 34*, National Sand and Gravel Association, August, 1949.
23. Fears, F. K., "Determination of Pore Size of Four Indiana Limestones", *Thesis*, submitted to Purdue University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, February, 1950.